ACCELERATOR APPLICATIONS OF NEW NONLINEAR FERROELECTRIC MATERIALS*

P. Schoessow#, A. Kanareykin, Euclid Techlabs LLC, Solon, OH 44139, USA
A.Kozyrev, St.Petersburg Electrotechnical University "LETI", St.Petersburg, Russia
V. P. Yakovlev, Omega-P, Inc., New Haven, CT, USA

Abstract

Materials possessing large variations in the permittivity as a function of the electric field exhibit a rich variety of phenomena for electromagnetic wave propagation such as frequency multiplication, wave steepening and shock formation, solitary waves, and mode mixing. New low loss nonlinear microwave ferroelectric materials present interesting and potentially useful applications for both advanced and conventional particle accelerators. Accelerating structures (either wakefield-based or driven by an external rf source) loaded with a nonlinear dielectric may exhibit significant field enhancements. Nonlinear transmission lines can be used to generate short, high intensity rf pulses to drive fast rf kickers. In this paper we will explore the large signal permittivity of these new materials and applications of nonlinear dielectric devices to high gradient acceleration, rf sources, and beam manipulation. We describe planned measurements using a planar nonlinear transmission line to study the electric field dependence of the permittivity of these materials. Nonlinear phenomena to be used as diagnostics include the appearance of harmonics with a cw drive signal and sharpening of a pulse waveform as it propagates.

INTRODUCTION

As one of the most promising techniques in the category of advanced accelerator concepts for high energy physics research applications, wakefield acceleration is being extensively investigated. In a wakefield accelerator, the field generated by a leading high charge drive beam (either a single bunch or bunch train) is used to accelerate a trailing "witness" bunch which contains a smaller amount of charge. The nature of this technology involves the ability to transport and control the high current drive beams required for its operation.

A dielectric wakefield device is a tube of dielectric surrounded by a conducting cylinder. The relatively small diameter of the device results from the high dielectric constant of the material used. The drive beam generates Cherenkov radiation as it passes through the DLA, coupling to the allowed modes of the structure.

If the permittivity of the dielectric decreases with the electric field strength (as it does in the ferroelectric materials considered here) then a number of interesting nonlinear effects occur. Harmonics are generated at higher frequencies than are present in the spectrum of the beam. Because the group velocity also increases with the electric field, high field portions of the wake outrun low field regions. As shown in Fig.1, a sharpening of the front end of the pulse and an increase in pulse amplitude occur. In other words, by transferring energy from low to high frequencies the nonlinearity acts to enhance the accelerating gradient of the wakefield device.

The properties of wakefields in a nonlinear dielectric waveguide were initially studied a number of years ago [1]. Numerical results showed that some wave steepening did occur and could act to enhance the wakefield acceleration gradient. Further development of these results into a working technology was hampered by the unavailability of suitable low loss, low permittivity dielectrics with fast response times and suitably high beam currents for wakefield experiments. A reexamination of the potential applications of nonlinear dielectric waveguides has been prompted by substantial progress in the area of microwave dielectrics, particularly ferroelectric-based ceramic materials.

A ferroelectric ceramic possesses an electric-field-dependent dielectric permittivity that can be rapidly varied by an applied bias voltage pulse. Ferroelectrics have unique intrinsic properties that make them extremely interesting for a number of high-energy accelerator and microwave applications. Response times of $\sim 10^{-11}$ sec for the crystalline form and $\sim 10^{-10}$ sec for ceramic compounds have been measured. Unlike semiconductors and plasma devices, ferroelectrics allow control of their dielectric properties in two directions using a single external control pulse, offering unique capabilities for high-power switching and tuning devices intended for accelerator and other rf applications [2, 3].

The use of the advanced barium-strontium-titanate-magnesium (BST(M)) composite ferroelectrics [4, 5] that have been developed by Euclid Techlabs [6,7] is currently being investigated. To date our research has focused on nonlinear response of the material to a dc bias field as a method of making tunable dielectric accelerating structures and fast rf switches [2, 8]. Experiments on switching times in these ferroelectrics have demonstrated rise times of the order of 1 ns, dominated by the capacitance of the switching circuit. A ferroelectric based fast 1.3 GHz tuner has been designed, fabricated and tested recently, and a time response has been demonstrated in the range of 30 ns, or 0.5 ns per degree of phase shift [9].

When ferroelectrics are used for tuning accelerating structures [6], the permittivity of a slab or cylindrical shell of the material is adjusted with an applied DC bias voltage. Typical values of the tunability (change in relative permittivity with a change in the electric field) are roughly 30% and can be up to 80% at 4-5 MV/m [7] with a reasonable loss tangent of 5×10^{-3} at X-band.

*Work supported by US DoE SBIR Program
#paul.schoessow@euclidtechlabs.com

The high dielectric constant of ferroelectrics (~500) is not desirable for many applications. For example, the use of high permittivity materials leads to enhanced wall losses in cylindrical geometries. Lowering the permittivity (and the loss tangent) through the use of ferroelectric-low loss tangent dielectric composites is the approach we are following. Recent theoretical work [4] has shown that ferroelectric composites can be designed that also preserve or even enhance the tunability of the material, and DC permittivities ~100 in nonlinear ferroelectric ceramics are feasible.

In the tunable devices studied so far by Euclid, the

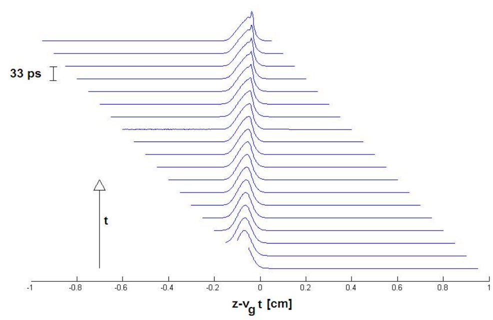

Figure 1: Gaussian pulse traveling down a planar waveguide loaded with a nonlinear dielectric. Note the steepening of the leading edge of the pulse and the growth of the amplitude of the pulse.

electric field of the rf signal is much smaller than the strength of the dc bias field used of to modify the average permittivity of the loading material. In these cases the rf field has a negligible additional effect on the permittivity. We consider here the large signal case where the permittivity of the ferroelectric loading of a dielectric wakefield structure or resonator is significantly affected by the strength of the rf field.

WAVE PROPAGATION IN NONLINEAR MEDIA

Fig.1 shows a numerical (FDTD) simulation of the transverse electric field of a short, initially Gaussian, high voltage pulse propagating on a 2D planar transmission line. The line is loaded with a nonlinear dielectric with properties similar to those shown in Fig.2. The thickness of the dielectric material in the line is 1 mm. The field is plotted at 33 ps increments and for clarity is shown as a function of $z - v_g t$, where the group velocity is $v_g \approx c\sqrt{\varepsilon(E=0)}$. Since the permittivity is a decreasing function of the field strength, the pulse center effectively outruns the leading edge of the pulse, eventually forming a discontinuity or shock. This phenomenon has two practical consequences: higher frequencies are generated and the magnitude of the field at the leading edge of the pulse increases (about a factor of two in the example shown). More complex waveforms evolve similar characteristics as they propagate.

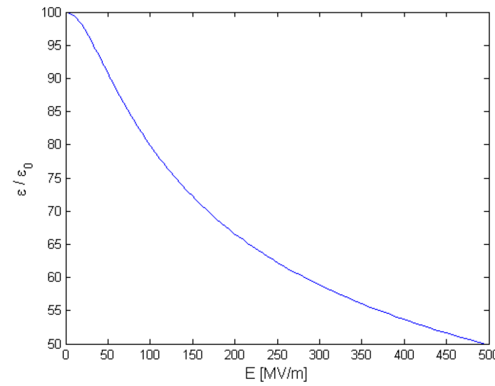

Figure 2: Relative permittivity as a function of electric field strength for a composite ferroelectric dielectric [4].

The nonlinear materials considered here are commonly characterized by the tunability n ≡ ε(E=0)/ε(E). A plot of the permittivity as a function of electric field obtained by inverting this expression is shown in Fig.2. We used this model to parameterize the results of the proposed shock line measurements for use in our wakefield device design simulations.

NONLINEAR TRANSMISSION LINE

Paraelectric film-based planar transmission lines (slot lines, coplanar waveguides) are broadband fast-acting tunable lines with relatively low losses (for BST composite films tan δ <10^{-2}, f = 1–10GHz) and suitable tunability (variation of the dielectric constant with applied field) [11]. Therefore they can be considered as candidates for use in UWB (ultrawideband) techniques (for pulse compression in particular).

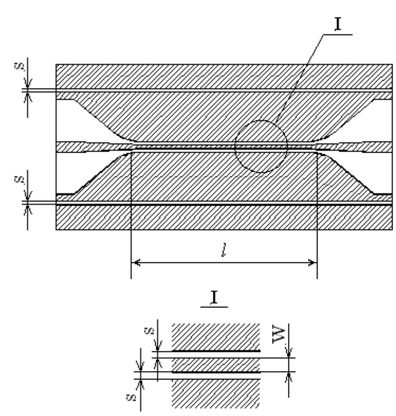

Figure 3: Schematic of a coplanar nonlinear transmission line [11] similar to what is planned for the nonlinear dielectric measurements. Crosshatched areas; copper; open areas: ferroelectric. Dimensions s = 20 µm, W = 40 µm, l = 6 mm.

Recently Findikoglu et. al [12,13] demonstrated at the low temperature the feasibility of the time expansion and time compression of short (nanosecond scale) electromagnetic signals, propagating along a coplanar waveguide fabricated from high-T_c superconductor electrodes on a single-crystalline $SrTiO_3$ substrate. These results showed the fundamental possibility of using dielectric nonlinearity for UWB pulse generation.

A transmission line bench test unit is being used for diagnosing the nonlinear properties of candidate ferroelectric-ceramic composites. Fig. 3 shows an example of a transmission line used for characterization of ferroelectric films [11]. The high voltage test pulse is applied to the central conductor. The outer slits serve as dc breaks so that a bias voltage can be applied between the central conductor and the ground pads if desired.

Analysis of transformation of the shape (including the formation of a shock wave) of a transient rf pulse propagating along the line makes it possible to obtain the time and frequency domain measurements of the generated harmonics over a broad frequency range for E-fields of varying magnitudes. A factor of 10 compression (from 130ns to 13ns) of the leading front of a pulse has been demonstrated in ref. [14] for a ceramic ferroelectric for a pulse with a peak electric field E~1V/μm. The nonlinear properties of ferroelectric ceramics with advanced composition and construction with a pulser voltage of 5-10kV with nanosecond pulse time duration are currently being studied.

Besides the experimental investigation of the nonlinear response of ferroelectric ceramics to short pulses, two additional microwave techniques can be used to obtain the nonlinear characteristics of the BST ceramics and elements. The first is the measurement of the anharmonic response of a BST ceramic-loaded resonator to a pulsed microwave signal. The use of the pulse regime of the resonator excitation permits the separation of the effect of any temperature rise of the ferroelectric ceramic from heating under the action of microwave power from the nonlinear electric field effect on dielectric properties of BST. The nonlinear microwave parameters of the BST ceramic can be extracted using this technique. Investigations have showed that BST film overheating due to microwave energy dissipation should be taken into account when considering the microwave nonlinear properties of the BST structures. However for the low loss (tan δ (10GHz)=0.005) BST ceramics produced by Euclid Techlabs, the above mentioned limitation for high power applications can be referred to higher frequencies (above 20GHz). Note that the use of short microwave pulses (shorter than thermal time constant) also decreases the heating effect.

The second microwave technique is the direct measurements of harmonics generated due to ceramic element nonlinearity (intermodulation distortion (IMD) measurements). This technique provides the characterization of the ferroelectric ceramic nonlinearity by measurement of the IMD products generated in a ceramic-loaded resonator under the action of a continuous incident microwave signal having two frequency components. Results on the BST nonlinearity obtained from the IMD and microwave pulse measurements will allow us to obtain complete information about the nonlinear behavior of BST under elevated microwave power including the effects of thermal processes.

SUMMARY

Technologies based on nonlinear optical phenomena have had a significant impact in the laser field, where harmonic generation and other effects are routinely and productively used. Similar effects have been employed at rf frequencies where the nonlinear properties of ferrite loaded transmission lines have been used to produce short rf pulses at MHz frequencies. Some of the other potential applications of this technology are: rf sources for UWB radars; fast rf switches and phase shifters; fast rf kicker drivers. Substantial progress in the area of microwave dielectrics, particularly ferroelectric-based ceramic materials that have been developed by Euclid Techlabs, offers the possibility of extending the frequency range of nonlinear rf devices to X-band and above. Nonlinear structures may also find applications in rf sources for frequencies (such as sub-mm waves) not accessible by conventional technologies. Electromagnetic shock formation can be used to produce intense short broadband rf bursts. Finally, application of wave steepening/pulse compression effects in nonlinear waveguides to enhance the performance (gradient and efficiency) of wakefield accelerators is an exciting possibility.

REFERENCES

[1] P. Schoessow, *Proc. AAC-1989* p. 371

[2] V.P. Yakovlev, O.A. Nezhevenko and J.L. Hirshfield. PAC2003, Portland, p. 1150, 2003,

[3] V.P. Yakovlev, O.A. Nezhevenko, J.L. Hirshfield, and A.D. Kanareykin. AIP Conference Proceedings, Vol. 691(1), pp.187-196, 2003.

[4] V. Sherman *et al.*, *J. Appl. Phys.* **99**, 074104 (2006); A. Tagantsev *et al.*, *J. Electroceramics*, 11, 5–66, 2003

[5] G.A. Smolensky, *Ferroelectrics and Related Materials,* Academic Press, New York, 1981.

[6] A. Kanareykin *et al.*, *Proc. PAC 2005,* http://cern.ch/AccelConf/p05/PAPERS/TPAE061.PDF

[7] A. Kanareykin *et al.*, *Proc. PAC 2007*, http://cern.ch/AccelConf/p07/PAPERS/MOPAS087.PDF

[8] V.P. Yakovlev *et al.*, *EPAC-2006*, pp. 487-489, 2006.

[9] S.Kazakov, *et al. Proc. AAC- 2008,* AIP CP 1086

[10] A.Kozyrev, *et al.*, *Microelectronic Engineering* **29**, 1995 p.257

[11] T.Samoilova *et al. J. Appl. Phys.* 2001 90(11) p.5703

[12] A.T.Findikoglu *et al.*, *Appl. Phys. Lett.* 1999, 74(12), p.1770

[13] A.T. Findikoglu *et al.*, *Appl. Phys. Lett.* 2000, 77(22) p.3645

[14] G.Branch, P.W.Smith, *J.Phys. D: Appl. Phys.* **29** 1996, p.2170-2178